ω and ρ Photoproduction with an Effective Quark Model Lagrangian

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Abstract

An unified approach for vector meson photoproduction is presented in the constituent quark model. The s- and u-channel resonance contributions are generated using an effective quark vector-meson Lagrangian. In addition, taking into account π^0 and σ t-channel exchanges for diffractive production, the available total and differential cross section data for ω, ρ^0, ρ^+, and ρ^- photoproduction can be well described with the same quark model parameter set. Our results clearly indicate that polarization observables are essential to identify so-called "missing" resonances.

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One of the main goals of the vector meson photoproduction experiments is to search for so-called "missing" resonances, which have been predicted by theory but have not been established experimentally [1,8]. One possible explanation for this long-standing puzzle is that these states couple weakly to the πN channel, which has provided most information for N^* states until now, but decay strongly into channels like ρN and ωN. Encouraged by recent successful descriptions of pseudoscalar meson photoproduction [2] we propose the parallel approach to vector meson photoproduction starting with the effective Lagrangian

$$L_{eff} = -\bar{\psi}\gamma_\mu p^\mu \psi + \bar{\psi}\gamma_\mu e_q A^\mu \psi + \bar{\psi}\left(a\gamma_\mu + \frac{ib\sigma_{\mu\nu}q^\nu}{2m_q}\right)\phi_m^\mu \psi + \ldots \qquad (1)$$

where e_q (m_q) denote the quark charge (mass), A^μ the photon field, and where the quark field ψ couples directly to the vector meson field

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \overline{K}^{*0} & \phi \end{pmatrix} \qquad (2)$$

with momentum q^ν. The coupling constants a and b in Eq. 1 allow for the two possible couplings of the quarks to the vector mesons; they are free parameters to be determined by the data. Unlike the large mass difference between the π and η in the peudoscalar case, the ω and ρ states have nearly equal masses, thus isospin violations for the ω and ρ are relatively small. This encourages us to pursue an unified description of both ω and ρ photoproduction with a single set of parameters, where the vector mesons couple directly to the quarks inside the baryon.

We briefly outline our quark model approach to vector meson photoproduction below; a detailed derivation of the formalism is given in Ref. [3]. Based on the effective Lagrangian in Eq. 1; at tree-level there are s-, u- and t- channel contributions, thus the matrix element for the meson photoproductions can be written as

$$\mathcal{M}_{fi} = \mathcal{M}_t + \mathcal{M}_s + \mathcal{M}_u. \tag{3}$$

The derivation of the s- and u- channel contributions uses methods similar to previous calculations of pseudoscalar meson photoproduction [2]. We separate the s-channel contributions $\mathcal{M}_s$ in Eq. 3 into two parts; the s-channel resonances below 2 GeV and those above 2 GeV that are treated as continuum contributions. The electromagnetic transition amplitudes of s-channel baryon resonances and their mesonic decays have been investigated extensively in the quark model [6–9] in terms of helicity and the meson decay amplitudes. These transition amplitudes for s-channel resonances below 2 GeV have been translated into the standard helicity amplitudes [10] amplitudes in Ref. [3] in the harmonic oscillator basis. The framework of vector meson photoproduction in terms of the helicity amplitudes has been thoroughly investigated [10], and the various observables can be easily evaluated in terms of these amplitudes. The resonances above 2 GeV are treated as degenerate, since little experimental information is available on those states. Qualitatively, we find that the resonances with higher partial waves have the largest contributions as the energy increases. Thus, we write the total contribution from all states belonging to the same harmonic oscillator shell in a compact form, using the mass and to-

tal width of the high spin states, such as $G_{17}(2190)$ for the $n = 3$ harmonic oscillator shell.

The u-channel contributions $\mathcal{M}_u$ in Eq. 1 include the nucleon, the Δ resonance for ρ production, whose transition amplitudes are treated separately, and all other excited states. The excited states are treated as degenerate in this framework, allowing their total contribution to be written in compact form. This is a good approximation since contributions from u-channels resonances are not sensitive to their precise mass positions.

The t-channel exchange, $\mathcal{M}_t$, is proportional to the charge of the outgoing mesons and is needed to ensure gauge invariance of the total transition amplitude. In addition to the t-channel exchanges from the effective Lagrangian in Eq. 1, additional t-channel exchanges are required for ω and ρ^0 prodcution in order to account for the large diffractive behavior in the small scattering angle region. Using reasonable coupling constants Friman and Soyeur proposed [4] that such additional t-channel exchanges can be described using π^0 exchange in the case of ω photoproduction and dominantly σ exchange in ρ^0 photoproduction. Thus, we have also included the π^0 and σ exchanges for ω and ρ^0 production, respectively, but employed a form factor at the corresponding vertices that is given by the harmonic oscillator quark model wavefunction. This leads to two additional parameters, α_{π^0} and α_σ, associated with the harmonic oscillator strength for the π^0 and σ contributions. A detailed derivation of the π^0 exchange is given in Ref. [5].

We assume that the relative strengths and phases of each s-, u- and t-channel term are determined by the quark model wavefunction in the exact

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$SU(6) \otimes O(3)$ limit. The masses and decay widths of the s-channel baryon resonances are obtained from the recent particle data group [11]. The quark masses m_q and the parameter α for the harmonic oscillator wavefunctions in the quark model are well determined in the quark model, they are

$$m_u = m_d = 0.33 \quad \text{GeV}$$

$$\alpha = 410 \quad \text{MeV}. \tag{4}$$

The coupling constants for the π^0 and σ exchanges are taken from Ref. [4]. This leaves only the coupling constants a and b, and the parameters α_π and α_σ to be determined by the data.

In Fig. 1, we compare total cross section data for $\gamma p \to \omega p$ and the three channels in $\gamma N \to \rho N$ with our calculations. We did not perform a systematic fitting procedure due to the poor quality of the data. Our study suggests that

$$a = -1.7$$

$$b' = b - a = 2.5$$

$$\alpha_\pi = 300 \quad \text{MeV}$$

$$\alpha_\sigma = 250 \quad \text{MeV} \tag{5}$$

leads to good overall agreement with the available data. Our results for the s- and u- channel contributions alone are also shown for the reactions. In general, the contributions from the s- and u-channel resonances in ω and ρ^0 photoproduction account for only 20 to 40 percent of the total cross section, demonstrating the dominance of diffractive scattering in these processes. Nevertheless, in the case of ω photoproduction the quark model result exhibits

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some resonance structure around 1.7 GeV photon lab energy which comes from the $F_{15}(2000)$ state. A similar structure also appears in ρ^0 photoproduction, and additional contributions from the $F_{37}(1950)$, $F_{35}(1905)$, $P_{33}(1920)$ and $P_{31}(1910)$ resonances leads to a broader structure. Clearly, the presence of diffractive scattering complicates the extraction of the nucleon resonance contributions from the t-channel terms in the case of neutral vector meson photoproduction. Here, the photoproduction of charged vector mesons, ρ^- and ρ^+, presented in Fig. 1-c and 1-d, become very important. In these cases, the diffractive contributions are absent, and therefore, resonance contributions dominate the cross sections. Our numerical results for charged ρ production are in good agreement with the few available data, even though the poor quality of the data limit any conclusions that can be drawn. Note that the cross section for charged ρ production is smaller by about a factor of three compared to ρ^0 production. Once the t-channel terms are added as described above we also obtain a good description of the more numerous ω and ρ^0 production data.

The results for the differential cross sections for ω and ρ production are shown in Fig. 2. We find that the overall agreement with the available data for the differential cross sections is quite good as well. As expected, the π^0 and σ exchanges are responsible for the small-angle diffractive behavior, while the s- and u-channel resonances dominate the large momentum transfer region. We point out that ρ^- and ρ^+ production also shows some the diffractive behavior, although the size of the effect is smaller compared to ω and ρ^0 production. This behavior can be explained by t-channel ρ^- or ρ^+ exhanges, which are naturally generated by the effective Lagrangian in Eq. 1. The data in the reaction

$\gamma n \to \rho^- p$ are in very good agreement with the quark model predictions, indicating that the quark model wave functions appear to provide the correct relative strengths and phases among the terms in the s-, u- and t-channels.

While the shapes and magnitudes of the differential cross sections are well reproduced within our approach we find little sensitivity to individual resonances. For example, in the energy region of $E_\gamma \sim 1.7\mathrm{GeV}$, removing the $F_{15}(2000)$ state - one of the "missing" candidates - changes the cross section very little, indicating the differential cross section may not be the ideal experimental observable to study the structure of the baryon resonances. In contrast to the cross sections, the polarization observables show a more dramatic dependence on the presence of the s-channel resonances. To illustrate their effects we show, as an example, the target polarization for the four channels in ω and ρ production with and without the contribution from the $F_{15}(2000)$ resonance. We do not expect the quark model in the $SU(6) \otimes O(3)$ limit to provide a good description of these observables. However, it demonstrates the sensitivity of these observables to the presence of s-channel resonances. Fig. 3 shows that the $F_{15}(2000)$ resonance has the most dramatic impact on the ω channel while the effects on the ρ channels are smaller due to the contributions from the isospin 3/2 resonances, $F_{37}(1950)$, $F_{35}(1905)$, $P_{33}(1920)$ and $P_{31}(1910)$, which reduce the significance of the $F_{15}(2000)$ state. This shows that polarization observables are essential in analyzing the role of s-channel resonances.

In summary, this investigation presents the first attempt to describe ω and ρ meson photoproduction in a quark model plus diffractive scattering framework. It establishes the connection between the reaction mechanism and

the underlying quark structure of the baryons resonances. The crucial role played by the polarization observables in determining the s-channel resonance properties is demonstrated. Data on these observables, expected from TJNAF in the near future, should therefore provide new insights into the structure of the resonance $F_{15}(2000)$ as well as other "missing" resonances.

REFERENCES

[1] N. Isgur and G. Karl, Phys. Letts. **72B**, 109(1977); Phys. Rev. **D23**, 817(1981).

[2] Zhenping Li, Ye Hongxing, and Lu Minghui, Phys. Rev. **C56** 1099(1997).

[3] Q. Zhao, Z. P. Li, and C. Bennhold, nucl-th/9711061, submitted to Phys. Rev. **C**.

[4] B. Friman and M. Soyeur, Nucl. Phys. **A100**, 477(1996).

[5] Q. Zhao, Z. P. Li, and C. Bennhold, "Vector Meson Photoproduction with an Effective Lagrangian in the Quark Model II: ω Photoproduction", submitted to Phys. Rev. **C**.

[6] L. A. Copley, G. Karl and E. Obryk, Nucl. Phys. **B13**, 303(1969); R. P. Feynman, M. Kislinger and F. Ravndal, Phys. Rev. **D3**, 2706(1971).

[7] Le Yaouanc *et al*, Hadron Transitions in the Quark Model, (Gordon and Breach, New York, 1988); Phys. Rev. **D8**, 2223(1973); **D9**, 1415(1974).

[8] R. Koniuk and N. Isgur, Phys. Rev. **D21**, 1868(1980).

[9] F. E. Close and Zhenping Li, Phys. Rev. **D42**, 2194(1990); Zhenping Li and F.E. Close, *ibid.*, 2207(1990).

[10] M. Pichowsky, Ç. Şavklı, F. Tabakin, Phys. Rev. **C53**, 593 (1996).

[11] Particle Data Group, E. J. Weinberg, *et al*, Phys. Rev. **D54**, 1(1996).

[12] F. J. Klein, to appear on the Proceedings of the GW/TJNAF Workshop on

N^* Physics, (Washington, D.C.) 1997, F.J. Klein, Ph.D. thesis, University of Bonn (1996).

[13] H. R. Crouch *et al*, Phys. Rev. **155**, 1468(1967); Y. Eisenberg *et al*, Phys. Rev. **D5**, 15(1972); Y. Eisenberg *et al*, Phys. Rev. Lett. **22**, 669(1969); D. P. Barber *et al*, Z. Phys. **C26**, 343(1984); J. Ballam *et al*, Phys. Rev. **D7**, 3150(1973); W. Struczinski *et al*, Nucl. Phys. **B108**, 45(1976).

[14] P. Benz *et al*, Nucl. Phys. **B79**, 10(1974).

[15] D. P. Barber *et al*, Z. Phys. **C2**, 1(1979).

Figure Caption

1. The total cross section for (a): $\gamma p \rightarrow \omega p$, (b): $\gamma p \rightarrow \rho^0 p$, (c): $\gamma n \rightarrow \rho^- p$, and (d): $\gamma p \rightarrow \rho^+ n$. The short-dashed line in (a) and (b) corresponds to the contributions from the transition matrix elements generated with the effective Lagrangian in Eq. 1, while the dashed line in (c) represents to cross section for $t \leq 1.1$ GeV^2. The data in (a) and (b) come from Ref. [12](triangle) and Ref. [13](square). The data in (c) were taken with the restriction $t \leq 1.1$ GeV^2 given by Ref. [14], and the data in (d) come from Ref. [15].

2. The differential cross section for (a): $\gamma p \rightarrow \omega p$ at $E_\gamma = 1.675$ GeV, (b): $\gamma p \rightarrow \rho^0 p$ at $E_\gamma = 1.730$ GeV, (c): $\gamma n \rightarrow \rho^- p$ at $E_\gamma = 1.850$ GeV, and (d): $\gamma p \rightarrow \rho^+ n$ at $E_\gamma = 1.850$. The short-dashed line in (a) and (b) denotes the contributions from the terms generated by the effective

Lagrangian in Eq. 1. while the dashed line denotes the contributions from the diffractive processes. The experimental data in (a) and (b) come from Ref. [12], and in (c) come from Ref. [14].

3. The target polarization for (a): $\gamma p \to \omega p$, (b): $\gamma p \to \rho^0 p$, (c): $\gamma n \to \rho^- p$, and (d): $\gamma p \to \rho^+ n$ at $E_\gamma = 1.7\text{GeV}$. The short-dashed lines show the result without the contribution from the $F_{15}(2000)$.

(a) $\gamma p \rightarrow \omega\, p$

(c) $\gamma n \rightarrow \rho^- p$

(b) $\gamma p \rightarrow \rho^0 p$

(d) $\gamma p \rightarrow \rho^+ n$

$\sigma(\mu b)$

E_γ (GeV)

(a) $\gamma p \rightarrow \omega p$

(b) $\gamma p \rightarrow \rho^0 p$

(c) $\gamma n \rightarrow \rho^- p$

(d) $\gamma p \rightarrow \rho^+ n$

θ (deg)